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INTERPRETATION OF SC OBSERVATIONS IN SPACE DURING MAGNETIC STORMS

by

K. G. Ivanov

[USSR]

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SUMMARY

It is shown that simultaneous observations of the magnetic field and of space plasma at time of SC on 27 March 1961 satisfy the conditions at the front of an inclined magnetohydrodynamic shock wave. This constitutes an argument in favor of this sudden commencement being induced by a shock wave. It is assumed that the sharp decrease of the magnetic field in space during the SC of 2 December 1963 was conditioned by the passage of a tangential break, having formed at supersonic flow in interplanetary plasma of a corpuscular flux with force-free magnetic field.

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One of the hypotheses, currently drawn from for the explanation of SC of magnetic storms, is the assumption that these SC are caused by shock waves [1]. To verify this hypothesis by direct method we may utilize the simultaneous observations of the magnetic field and plasma in space at time of SC concurrently with the the correlations, linking the quantities at shock wave front. If, as result, the observed values satisfy these correlations, it can be used as an argument in favor of the shock wave hypothesis, as the cause of sudden commencements. However, it should be borne in mind during such a verification, that if shock waves exist

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* OB INTERPRETATSII NABLYUDENIY VNEZAPNYKH NACHAL MAGNITNYKH BUR' V KOSMICHESKOM PROSTRANSTVE.

they constitute specific collisionless shock waves, and the correlations at their fronts, may, generally speaking, differ from those in standard magnetohydrodynamic shock waves occurring on account of collision dissipation.

The deriving of correlations at the front of a collisionless shock wave is one of the problems of collisionless plasma physics, and its solution is at present available only in some particular cases. Thus, correlations at the front of a perpendicular wave within the bounds of strong shock waves were obtained in [2]. In the work [3] were obtained correlations at the front of a weak slant wave moving in a "cold" plasma, that is, a plasma where the gas pressure is less than the magnetic pressure. The striking feature of the solutions obtained is the fact, that they coincide in shape with the correlations at the front of standard hydromagnetic shock waves, with the exception that instead of instantaneous values of the quantities behind the front, their mean values are used. This circumstance generated the assumption, that the conditions at front in collisionless plasma coincide also for slant shock waves with the conditions for standard hydromagnetic waves as well as in form; (see [4-6]). These conditions are particularly well utilized in [6] for the analysis of physical conditions behind the front of an outgone shock wave, occurring at plasma supersonic flow past the Earth's magnetosphere. It appears to be possible to utilize the same conditions for the analysis of sudden commencements in space.

If it is found that the quantities, observed prior to SC and immediately afterward, satisfy the correlations at the front of a strong slant magnetohydrodynamic shock wave, the fact could serve as an argument to the effect that SC are induced by shock waves, and thus, the result of the very strict conclusion in regard to conditions at front of a strong slant collisionless shock wave will be anticipated.

Let us utilize here the conditions at front of a slant shock wave and the method for their solution according to [7], alongside with the well known data of observations of SC in space [8 — 13]. Let us, first of all, provide a characteristic to the experimental material. Five cases of SC observations in space to which SC on Earth's surface were compared, have been presented in literature. These data are inhomogenous from the standpoint of observations, as well as publications. Thus, during the SC of 27 March 1961, absolute observations of the magnetic field were conducted and the plasma flux was measured; at the same time, it was possible to judge on the magnitude and direction of plasma velocity and of its concentration. Full information on the magnetic field, prior and after SC, and the full data on plasma flux magnitude after SC in several bands are presented in the works [8, 9]. These data are of better value to this work than those of other observations. Indeed, at time of SC on 30 November 1961, Explorer-XII was situated between the outgone wave and the boundary of the magnetosphere in a region, where the fluctuations of the magnetic field were of the order of its variation during SC [11], which did not allow to register the SC in the magnetic field.

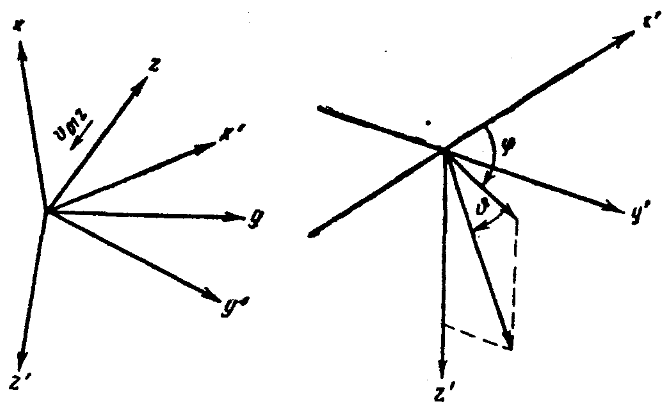

Fig. 1

Observation data on SC of 7 October and 4 December 1962 on Mariner-2 do not include the complete information on the magnetic field, since no absolute measurements of the radial component of the magnetic field (along the line Sun-rocket) were conducted in that experiment [14]. Observation data of the SC on 2 December 1963 on Explorer-XVIII include the complete information on the magnetic field [13]. However, we were not made aware to-date of publication of data on plasma during that SC. Analysis of observations of the SC of 27 March 1961 on Explorer-X is presented below.

According to [7], the conditions on a slant shock wave, written in dimensionless form and in a system of coordinates **xyz** (Fig. 1), in which the motion on both sides of the shock front is plane (the origin is placed on the shock front, the axis **x** is directed along the external normal to the front, the axis y is directed along the tangential component of the magnetic field and the point O moves along the front with a velocity v_{01z}, where v_{01z} is the z-component of plasma velocity ahead of the shock front), have the form

$$(h_2-h_1)\{(\gamma-1)Z^2+(2-\gamma)h_1Z+1\}- \tag{1}$$

$$-2\{h_1Z^2-(h_1^2+\gamma P_1-1)Z-h_1\}=0, \tag{2}$$

$$\eta=h_1Z+1/h_2Z+1,$$

$$z=\frac{P_2-P_1}{h_2-h_1}+\frac{h_2+h_1}{2}, \tag{3}$$

$$v_{x1}^{*2}=h_2-h_1/\eta h_2-h_1, \tag{4}$$

$$v_{y2}^*-v_{y1}^*=h_2-h_1/v_{x1}^*, \tag{5}$$

where $h, \eta, P, \mathbf{v}^*$ are dimensionless quantities, equal to [*] where $H, \rho, \mathbf{v}, p$ are respectively the magnetic field, the density, the velocity and the pressure of the plasma. The index i takes, respectively ahead and behind the front, the values of 1 and 2. Note that

$$p_i=n_ikT_i,\ \rho_i=n_iM,\ \mathbf{v}_i=-(\mathbf{D}-\mathbf{v}_{0i}), \tag{7}$$

where n, T are the temperature and concentration of plasma; M is the mass of a proton; D and $\mathbf{v}_{0i}$ are respectively the velocity of the shock front and of the plasma in a system of coordinates, fixed relative to the satellite, and whose axes are parallel to the corresponding axes of the system x y z.

The conditions (1) – (5) are supplemented by the condition of normal component continuity, which is easier to utilize by writing it with the aid of dimensional quantities

$$H_{x1}=H_{x2}\equiv H_x. \tag{8}$$

Let us admit the following order of resolution of conditions (1) – (5), (8). The quantities $H_{yi}, H_x, n_1, T_1, v_{01x}, v_{01y}, v_{01z}$ are considered given; then, the quantities searched for and determined by (1) – (5) will be $n_2, T_2, \mathbf{D}, \mathbf{v}_2$. Subsequently, by the computed values of $n_2, \mathbf{v}_2$ and T_2 we shall estimate the plasma flux immediately after the SC and compare it with the observed flux. If the computed and the observed fluxes, ressectively S and S_0 are close in magnitude, it may serve as an argument to the effect that the SC of 27 March 1961 was caused by a shock wave.

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[*] insert at the end of line 10 page 4 :

$$h_i=\frac{H_{yi}}{H_x},\quad \eta=\frac{\rho_1}{\rho_2},\quad P_i=\frac{4\pi p_i}{H_x^2},\quad \mathbf{v}_i^*=\frac{\mathbf{v}_i(4\pi\rho_1)^{1/2}}{H_x}. \tag{6}$$

We shall determine preliminarily $H_{yi}, H_x, v_{01x}, v_{01y}$ and v_{01z} through the directly observed quantities $H_1, H_2, \varphi_1, \vartheta_1, \varphi_2, \vartheta_2, \mathbf{v}_{01}$ ($\mathbf{v}_{01}$ is taken radially directed from the Sun, which should not lead to a significant error in the direction of plasma velocity [9], Fig.1). Evidently,

$$H_x = H_i(l_i l_x + m_i m_x + n_i n_x),\ H_{yi} = H_i(l_i l_y + m_i m_y + n_i n_y), \qquad (9)$$

where l_i, m_i, n_i are the directing cosines of the vectors $\mathbf{H}_1$ and $\mathbf{H}_2$ in the system of coordinates $x'y'z'$ (Fig.1), of which the origin is on the satellite, the axis x' is directed at the Sun, the axis z' at the South pole of the ecliptic (the angles φ, ϑ are given in that system of coordinates); $l_x, m_x, n_x, l_y, m_y, n_y$ are the directing cosines of axes x (normals to the shock wave front) and y (tangential component of the magnetic field) in the system of coordinates $x'y'z'$. It is evident that

$$l = \cos\varphi\cos\vartheta,\ m = \sin\varphi\cos\vartheta,\ n = \sin\vartheta. \qquad (10)$$

By the strength of the condition (8)the perturbation vector of the magnetic field

$$\mathbf{h} = \mathbf{H}_2 - \mathbf{H}_1 \qquad (11)$$

collinear with the tangential components of the field H_{yi}, which gives

$$l_y = \frac{H_2 l_2 - H_1 l_1}{A},\quad m_y = \frac{H_2 m_2 - H_1 m_1}{A},\quad n_y = \frac{H_2 n_2 - H_1 n_1}{A} \qquad (12)$$
$$A = \{(H_2 l_2 - H_1 l_1)^2 + (H_2 m_2 - H_1 m_1)^2 + (H_2 n_2 - H_1 n_1)^2\}^{1/2}.$$

The condition

$$\mathbf{H}_x = \mathbf{H}_1 - \mathbf{H}_{y1} \qquad (13)$$

allows to determine the directing cosines of the normal to the shock wave front

$$l_x = \frac{H_1 l_1 - H_{y1} l_y}{B},\quad m_x = \frac{H_1 m_1 - H_{y1} m_y}{B},\quad n_x = \frac{H_1 n_1 - H_{y1} n_y}{B}, \qquad (14)$$
$$B = \{(H_1 l_1 - H_{y1} l_y)^2 + (H_1 m_1 - H_{y1} m_y)^2 + (H_1 n_1 - H_{y1} n_y)^2\}^{1/2}.$$

The directing cosines of the external normal are either chosen by the results (14), or by the variation by 180° of the direction so as to satisfy the obvious physical condition that the shock wave has a radial velocity component directed from the Sun. It is evident that the velocity components ahead of the shock wave are

$$v_{01x} = v_{01}(l_x l_v + m_x m_v + n_x n_v),$$
$$v_{01y} = v_{01}(l_y l_v + m_y m_v + n_y n_v), \qquad (15)$$
$$v_{01z} = v_{01}(l_z l_v + m_z m_v + n_z n_v),$$

where l_v, m_v, n_v are the direction cosines of $\mathbf{v}_{01}$, given in the form $l_v = -1$, $m_v = n_v = 0$; l_z, m_z, n_z are the direction cosines of the axis z in the system of coordinates $x\,y\,z$. They may be determined through the Eiler angles

$$l_z = \sin\theta\cos\Psi,\ m_z = -\sin\theta\cos\Psi,\ n_z = \cos\theta. \qquad (16)$$

The Eiler angles (θ is the mutation angle, Ψ is the precession angle and Φ is the angle of the specific rotation) are in their turn determined by the known m_x, n_x, n_y

$$m_x = \sin\Psi\cos\Phi + \cos\theta\cos\Psi\sin\Phi,$$
$$n_x = \sin\theta\sin\Phi,\ n_y = \sin\theta\cos\Phi. \qquad (17)$$

Therefore, $H_{y1}, H_x, H_{y2}, v_{01x}, v_{01y}, v_{01z}$ are determined with the help of (9) – (17), and the quantities n_1, T_1, v_{01} are given as the average for two hours prior the SC [9]. h_1 and P_1 are determined on the basis of (6). The condition (1) allows the finding of Z.- η, P_2, v_{x1} are respectively found on the basis of (2) – (4). Formulas (6), (7) allow the finding of n_2, T_2, D, v_{02x}. Finally, we find v_{02y} by (5) and (6).

We shall estimate the plasma flux immediately after SC by the formula

$$S = n_2 v_{02}\cos\alpha, \qquad (18)$$

where α is the angle between the vector $\mathbf{v}_{02}$ and the normal $\mathbf{n}$ to the trap inlet

$$\cos\alpha = l_{v2}l_n + m_{v2}m_n + n_{v2}n_n. \qquad (19)$$

The direction cosines of plasma velocity behind the front are

$$l_{v2} = \frac{v_{02x'}}{v_{02}},\quad m_{v2} = \frac{v_{02y'}}{v_{02}},\quad n_{v2} = \frac{v_{02z'}}{v_{02}}, \qquad (20)$$

where

$$v_{02x'} = v_{02x}l_x + v_{02y}l_y + v_{02z}l_z,$$
$$v_{02y'} = v_{02x}m_x + v_{02y}m_y + v_{02z}m_z, \qquad (21)$$
$$v_{02z'} = v_{02x}n_x + v_{02y}n_y + v_{02z}n_z,$$
$$v_{02} = (v_{02x}^2 + v_{02y}^2 + v_{02z}^2)^{1/2},\quad v_{02z} = v_{01z}$$

(primes indicate that the components of velocity are considered in the system of coordinates $x', y'z'$) ; l_n, m_n, n_n are the direction cosines of the normal to the inlet of the trap

$$l_n = \cos\varphi_n \cos\vartheta_n, \; m_n = \sin\varphi_n \cos\vartheta_n, \; n_n = \sin\vartheta_n, \qquad (22)$$

where φ_n, ϑ_n are the angles determining the position of the normal n in space, when it is closest to the direction antiparallel to the velocity v_{02} (these angles are determined according to Fig. 12 of [9], when the angles φ_v and ϑ_v, defining this antiparallel direction are known).

The angles φ_v and ϑ_v are determined from the conditions

$$-l_{v2} = \cos\varphi_v \cos\vartheta_v, \; -m_{v2} = \sin\varphi_v \cos\vartheta_v, \; -n_{v2} = \sin\vartheta_v. \qquad (23)$$

Let us bring forth numerical values for the considered case of SC (27 March 1961). The initial data are

$$H_1 = 11\gamma, \; \varphi_1 = 20^\circ, \; \vartheta_1 = 45^\circ, \quad n_1 = (4 \pm 1)\ \text{см}^{-3}; \; v_{01} = (280 \pm 20)\ \text{км/sec.};$$
$$H_2 = 22\gamma, \; \varphi_2 = 35^\circ, \; \vartheta_2 = 20^\circ; \quad \gamma = 1.6.$$

The quantities determined on the basis of (8) — (17) are

$$\begin{array}{lll} -l_x = -0{,}28, & l_y = 0{,}72, & l_z = 0{,}66, \\ -m_x = 0{,}26, & m_y = 0{,}70, & m_z = -0{,}66, \\ -n_y = -0{,}93, & n_y = -0{,}02, & n_z = -0{,}37, \end{array}$$

$$H_x = 8{,}5\ \gamma, \quad H_{y1} = 7\gamma, \quad H_{y2} = 20\gamma; \quad v_{01x} = 78, \quad v_{01y} = -202,$$
$$v_{01z} = -185\ \text{км/sec.}$$

The quantities, computed on the basis of (1) — (17) and (19)- (21) are

$$\begin{array}{llll} l_{v2} = -0{,}89, & l_n = -0{,}89, & n_2 = 9\ \text{см}^{-3}, & D = 328\ \text{км/sec.} \\ m_{v2} = 0{,}24, & m_n = -0{,}16, & T_2 = 1{,}0 \cdot 10^6, & \alpha = 52^\circ, \\ n_{v2} = -0{,}38, & n_n = 0{,}34, & v_{02} = 324\ \text{км/sec} & S = 1{,}8 \cdot 10^8\ \text{см}^2/\text{sec.} \end{array}$$

The computed value of the flux is $\sim 1.8 \cdot 10^8$ cm^2 sec^{-1}, while that, observed immediately after SC, was $\sim 2.6 \cdot 10^8$ cm^2 sec^{-1} [9], that is, a good agreement exists between the computed and the observed values. The discrepancy between them is within the limits of precision of the determination of S by (18). Indeed, the error of the latter is equal to the sum of the errors of n_2, v_{02} and $\cos\alpha$. But these last ones are at least equal respectively to the mean errors of n_1, v_{01} and v_{01} that is, according to [9], 25, 7 and 7 percent, which gives to the mean random error S a value equal to 40 percent. This means, that during the calculation of the flux by (18), we may obtain a value deflecting from the observed one by ± 1, which agrees with the deflection value of the computed flux from the observed one, equal to 0.8.

Thus, simultaneous observations of the magnetic field and plasma in space during SC of 27 March 1961 satisfy the conditions at the front of a slant shock wave. This means, that the sudden commencement was induced by the shock wave.

It should, however, be noted, that experimental as well as theoretical data are presently available, showing that SC in space are not only induced by shock waves but also by certain other causes. Thus, space observations during the SC of 2 December 1963 [13] cannot be understood within the framework of the theoretical scheme based upon the assumption of the shock wave, as during that SC, a sign change of the magnetic field was observed, whereas in a collisionless plasma, just as is the case in standard magnetohydrodynamics, only shock waves, in which the sign of the tangential component of the magnetic field is invariable, are evolutionary.

In connection with this considerable interest is aroused by the hypothesis of corpuscular streams with force-free magnetic fields, according to which [15] SC set in space at time of flux's own magnetic field passage through the place of satellite or rocket location. At the same time, depending upon the orientation of the stream's field at time of SC, increase or decrease of the magnetic field can be observed, which provides the possibility to explain the fact of field decrease at time of SC on 2 December 1963. Concretizing this hypothesis in the part referring to SC, one may notice, that inasmuch as the corpuscular stream with its own field move at supersonic velocity, all the phenomena observed in the near-Earth space can be also observed in its vicinity, that is, such phenomenas as the formation of a sharp boundary between the magnetic field of the stream and the interplanetary plasma and the formation of the outgone wave.

The satellite (rocket) encounter with the outgone shock wave and the tangential break at the boundary plasma — stream's magnetic field, can lead to sharp variations of the observed magnetic field, interpreted as sudden commencements and sudden impulses. The SC of 2 December 1963, in particular, could have occurred as a result of passage of the tangential break. On such a break the condition of equality of the generalized pressure on both sides of the break must be satisfied [7]. That is why in the presence of data on plasma during the SC of 12 December 1963, a direct verification of this assumption can be made.

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*** THE END ***

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REFERENCES

[1].- T. GOLD.- Gas dynamics of cosmic clouds. North Holl.P.Co.Amsterdam, 1955.

[2].- P. L. AUER, H. HURWITZ, R. W. KILB.- Phys.Fluids, 5, 298, 1962.

[3].- V. I. KARPMAN.- ZhTF, 33, 959, 1963.

[4].- P. J. KELLOG.- J. Geophys. Res. 67, 3805, 1962.

[5].- P. D. NOERDLINGER.- Ibid. 69, 369, 1964.

[6].- G. K. WALTERS.- Ibid. 69, 1769, 1964.

[7].- A. G. KULIKOVSKIY, G. A. LYUBIMOV.- Magnitnaya gidrodinamika (Magnetohydrodynamics).- Fizmatgiz, 1962.

[8].- J. P. HEPPNER, N. F. NESS, C. S. SCEARCE, T. L. SKILMAN.- J.Geophys.Res. 67, 5001, 1962.

[9].- A. BONETTI, H. S. BRIDGE, A. J. LAZARUS, B. ROSSI, F. SCHERB.- Ibid. 68, 4017, 1963.

[10].- R. A. HOFFMAN, L. R. DAVIS, J. M. WILLIAMSON.- Ibid. 67, 5001, 1962.

[11].- L. J. CAHILL, P. G. AMAZEEN.- Ibid. 68, 1835, 1963.

[12].- C. W. SNYDER, M. NEUGEBAUER.- Cospar, Florence, 1964.

[13].- N. F. NESS, C. S. SCEARCE, J. B. SEEK.- Ibid. Florence 1964.

[14].- P. J. COLEMAN, L. DAVIS, E. J. SMITH, C. P. SONETT., Science, 138, 1099, 1962.

[15].- E. I. MOGILEVSKIY.- Geomagnetizm i Aeronomiya, 2, 48, 1962.

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